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# An overview of photovoltaic thermal combination (PV/T combi) technology

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ABSTRACT

Solar energy is the most recognised diversified renewable energy from which the production can be extracted into electrical and thermal energy. Hybrid PV/T technology is a combination of photovoltaic panel and thermal collector. Photovoltaic panel converts sunlight to electricity, while thermal collector converts solar energy directly to heat. The synchronization led to the development of PV/T air-based and PV/T water-based systems. This paper presents an overview of Photovoltaic Thermal Combination system (PV/T Combi), with a combination of photovoltaic panel with air- and water-based systems as one unit. This bi-fluid concept not only generates electrical energy, but also produces hot air and hot water, simultaneously. From the literature, this concept was seen to achieve better overall energy efficiency, especially in electrical production. This is because heat is extracted from the PV module double by both air and water media. The combination of these two types of heat carrier is to cover the limitations and weaknesses of independent PV/T water and air heat collector systems. The configuration of the system also introduced low-cost cooling effect such as fins and ribs. The system is analysed in both mathematical modelling and experimental testing methods. The outcome of the system can benefit humankind due to its efficient application in domestic and industrial sectors.



**Contents**



## 1. Introduction

Energy is the key role of all life kind activities. It has become a crucial demand in modern economy. In practice, nation development can be measured by its energy consumption. As the country population progress, the energy consumption increases. Energy is also predicted to be one of the most challenging and major issues of the world in future time [1–4]. For the past few decades, fossil fuel has been providing major contribution, which estimated up to 80% of energy production to the world [5]. This reliable energy provides the service and engineering to the society in terms of improving lifestyle, advanced transportations, cutting-edge communications, vanguard medical aid and many more.

The demand of energy consumed by humankind has been growing significantly over the past 30 years. It was recorded back

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on 1980–2010 that the total primary energy consumption has massively increased to 75–80% [6,7]. Due to this overwhelming demand and reports by numerous oil analysts, the source of fossil fuels is getting depleted. It is evidenced in Fig. 1 that the production is globally at an all-time historical high [8–10]. From this bell-shaped curve graph, the production of oil and natural gas is seen to have rapidly increased. After a peak in 2015, thereafter the production seems to have declined and developed decreasing trends towards 2050.

On the other hand, the rapid energy ingestion also leads to uncontrolled carbon dioxide ($CO_2$) emission as well as pivotal global warming [11]. Fossil fuel contributes to long-term environmental issues such as acid rain and greenhouse effect [12]. These phenomena are very crucial and become a major environmental concern crisis. Supported by meteorological data, the world is getting warmer by 0.8 °C every six hours [13]. This eventually integrates severe natural greenhouse gases such as nitrous dioxide ($NO_2$), methane, chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs). Zain-Ahmed et al. [14] noted that the influence of Earth's surface temperature to $CO_2$ emissions at the atmosphere has a proportionality function of both parameters. This can be referred in Fig. 2. As the year increases, the Earth's temperature and $CO_2$ emission are drastically increased. Worse still, these circumstances caused natural disasters such as cataclysmic volcano eruption, earthquake, tsunami, flash flood and other disasters which caused deaths by thousands.

To mitigate the climate change issues, scientists are looking into alternative energy resources. Policymakers are advocating de-emphasising nuclear energy and focusing on other alternatives [15]. This corresponds to the wake of Fukushima double disasters and oil price volatility. In addition to that, political crisis unrest in Middle East countries has further escalated global oil production. Researchers around the world have been challenged to come up

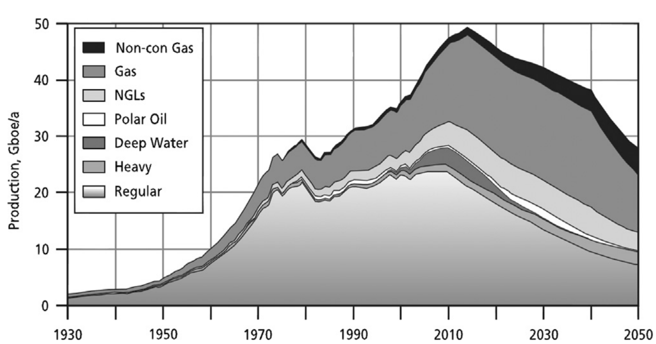


**Fig. 1.** The production of oil and gas and prediction in future [8].

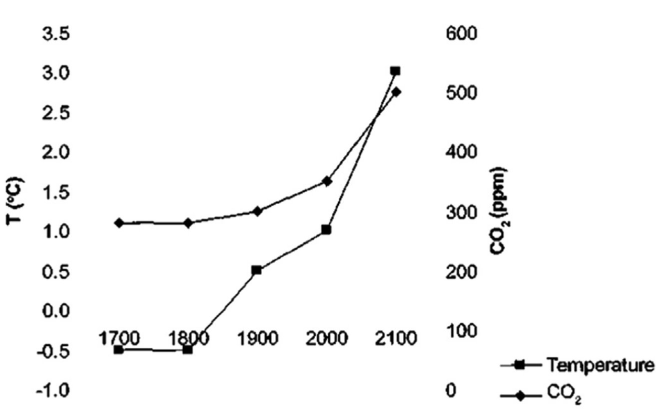


**Fig. 2.** Relationship between Earth temperature and $CO_2$ emissions [14].

with environmental-friendly energy resources. In this sense, renewable energy (RE) is a promising candidate to rectify this critical phenomenon that the world is facing. RE is a naturally replenished resource of energy that is derived from solar, wind, geothermal, hydroelectric as well as biomass action [16]. Due to its infinite source, RE has received huge attention across the world for its noiseless technology, cost effectiveness, reliable energy source, and most of all it is environmental friendly engineered.

In 2006, RE technology was described to contribute 13.3% from the world's primary energy needs [17]. The percentage is still considered low due to some challenges such as exploiting local available resources, overcoming environmental issues, public acceptance and worldwide policy. However, it is also predicted that the contribution of renewable energies will rise up from 20% (in 2011) to 28% (in 2030) [18]. This alternative energy is the best option that will increase the variety in energy resources. It may solve some of the following problems: (1) replace fossil resources, (2) decrease foreign dependency in fossil fuel as it is domestic, (3) prove important in electric supply, especially in rural areas, and (4) solve the air pollution caused by hazardous gases.

Solar energy is one of the environmentally compatible sources of renewable energy. It is most recognised as one of the promises that can conserve the Earth to survive in a reasonable shape. Solar energy is virtually unlimited. The Sun is the primary source of renewable energy and it harvest more abundant than any other type of energy. Furthermore, other renewable energies are limited in their quantity. The Sun can be assimilated in a major form of heat and light energy. The technology of harvesting solar energy can be derived into the following three main categories:

1. Solar thermal system: Captured heat from solar collector is directly converted solar energy into thermal energy. The output energy can be used for domestic hot water, space heating, agricultural drying and increased ventilation [19].
2. Photovoltaic (PV) system: A PV module is directly converted sunlight captured from the panel to electricity energy in direct current (DC) form through the photoelectric effect. This output is specifically used for electricity generation [20].
3. Photovoltaic-Thermal (PV/T) system: A combination system between solar thermal and photovoltaic components. Sunlight, which in the form of photon energy, is absorbed to the system. It is able to generate electricity and some part of it is converted to heat energy. The conversion process occurs simultaneously [21].

The effectiveness of solar thermal and PV system to harvest the absorbed sunlight is measured by its output efficiency. Magnificent results have shown a great performance and higher efficiency of PV/T by 50–80% compared to single PV and thermal collector. It is contrary with the usage of electrical energy which is 95% more needed than thermal energy. The commercial PV modules claimed by the manufacturer were recorded to achieve efficiency in a range of 6–16% at temperature 25 °C [22]. This relatively low efficiency is much smaller compared to thermal efficiency. The production of electricity on PV technology causes heat generation as well, which has a great influence on the dropping performance of electrical yield. Study carried out by Othman et al. [23] reported that for every 1 °C increase in PV panel, there is about 0.4–0.5% decrement in its efficiency. The statement is supported by below equations. The short circuit current ($I_{sc}$) and open circuit voltage ($V_{oc}$) equations show the relationship towards temperature dependence [24]. By calculation, it is showed that for typical silicon-based PV, the cell efficiency will drop 0.5% by 1 °C temperature increment.

$$I_{sc} = I_o\left[\exp\left(\frac{qV_{oc}}{kT}\right) - 1\right] \tag{1}$$

$$\frac{dV_{oc}}{dT} = -\frac{V_{g0} - V_{oc} + \gamma\left(\frac{kT}{q}\right)}{T} \tag{2}$$

where $I_o$=diode saturation current; $k$=Boltzmann constant; $q$=element charge; $\gamma$=temperature dependency parameter

PV/T system was introduced in the middle of the 1970s to minimise the losing efficiency on a PV module. The system not only produces electricity but also acts as a thermal absorber. It implements a simultaneous cooling system using air or water as the heat exchanger carrier. The medium type acts as a heat carrier and is chosen based on its usage, which depends on building thermal needs, weather conditions as well as system operation by monitoring the temperature level and heat removal type [25]. In 2001, photovoltaic–thermal combination of air and water mode system (PV/T Combi) was introduced by Tripanagnostopoulos at 17th European PV Conference, Germany. The idea to combine both heat transfer medium is to increase the absorption process on the module. Consequently, PV module will reach its optimum performance.

The objective of the paper is to provide an overview of the design and performance of the PV/T Combi system which has been studied by several researchers. To date research on the Combi system is just a number which might be due to certain reasons. There is still no review paper compiling the PV/T Combi system study yet. It is hoped to inject some ideas to other researchers to work on it and improve any leakage aspects of the system. In the following section, the paper provides a discussion on factors and contributions that the system can supply. Also, there is a brief review on the previous and latest development work of PV/T air and water-based system, which gives idea on the combination of both medium of heat exchangers (Section 2).

## 2. Initial development on PV/T collector: design and performance evaluation

The study of PV/T system started in the middle of the 1970s. It was initiated when PV module faced a drop in efficiency when the temperature of the surface panel is increased. Martin Wolf was known to be the first to introduce work on flat-plate PV/T liquid-based system [26]. The study was tested for residential heating at Boston, which covered 50 m$^2$ area. A silicon solar array mounted on a non-concentrating thermal collector is equipped with lead-acid battery and water tank for electricity and thermal storage, respectively. The finding showed the combination system is technically practicable and cost effective. This pioneering study was further developed with mathematical modelling by Florschuetz, which was focused on TRNSYS application. The performance of flat-plate PVT liquid system was analysed using the modification of the Hottel–Whillier thermal model based on cell array efficiency and decreasing cell efficiency with temperature [27–28]. It then became the basis of the PV/T model TYPE 50 in TRNSYS.

Among the early work, Kern and Russell also innovated the idea of combining the PV/T system in order to remove the heat on the PV surface so that the efficiency can be improved [29]. The experiment was performed using two types of coolant medium separately, which were the medium of air and water. A theoretical approach on PV/T systems using conventional thermal collector technique was also presented by Hendrie [30]. The mathematical model analysed the performance of a combined PV/T system for air and liquid based systems. The results showed a very low efficiency electrical performance of 6.8% compared to a thermal output of 40.4% and 32.9% for air- and liquid-based systems, respectively.

During the 1980s, research and development of PV/T system was performed rapidly. As shown in Fig. 3, there were vigorous studies covering various methods in order to gain better performance system to meet the application needs. PV/T system is analysed using monocrystalline, polycrystalline, amorphous or thin film cells [31–35]. These variations of solar cells have their own extra features based on their performance and also production cost. To capture maximum solar radiation, three classes of concentrator were presented. The first class, which also is of interest by researchers, is flat plate and compound parabolic concentrator (CPC) [35–42]. Figs. 4 and 5 show examples of CPC design by different researchers.

Second class consists of linear parabolic reflector and linear Fresnel reflector and the third class consists of 3D Fresnel lens [43–46]. The second and third classes are not chosen for most studies because of the complicated construction and maintenance issues. It is also mainly focused on the development of building integrated PV/T (BIPVT). The type of covered panel also is discussed between glazed and unglazed PV panels [47,48]. It is found that the glazed PV modules have higher thermal efficiency than unglazed panels. But both types of covered panels experienced a very low electrical efficiency due to the additional optical losses. Another field of study exploring the PV/T system is the type of fluid flow. It is classified as natural, forced or laminar fluid flow [49,50]. They show a satisfactory result on enhancing airflow on the PV surface to decrease temperature and increase electrical generation.

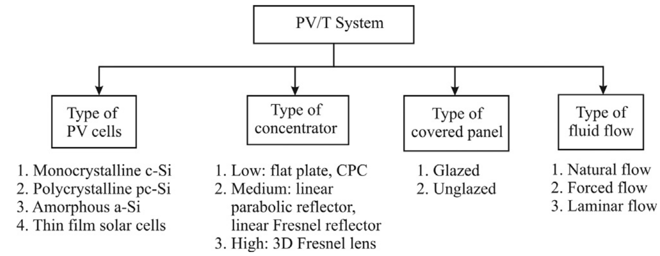


**Fig. 3.** General classification of a PV/T system.

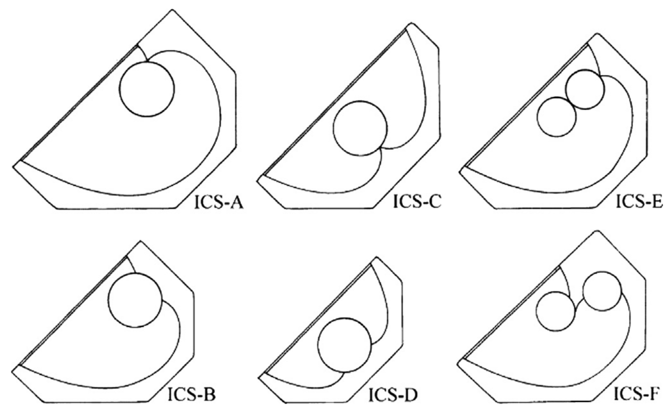


**Fig. 4.** Integrated collector storage (ICS) of different CPC designs with one or two cylindrical storage tanks [40].

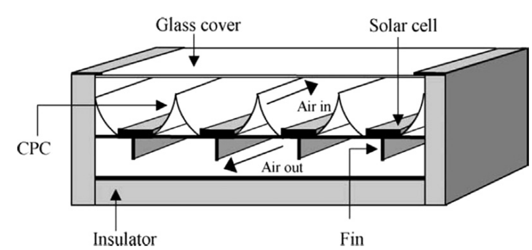


**Fig. 5.** Schematic model of a double-pass photovoltaic thermal solar collector with CPC and fins [41]. Indication of diffuse reflected radiation on the PV panel [36].

At an early stage, PV/T technology is mostly focused on air-based systems. This is due to its easier set up and low cost, both on construction and on operation as well as cost-effective solution for BIPVT system. Several designs have been presented which include the single and dual channel [41,51–53], glazed and unglazed air pass [47,48], and several possible approaches to enhance the cooling effect. This includes attached fins underneath the PV panel, V-groove absorber, rectangular tunnel and hexagonal honeycomb heat exchanger [23,54–57]. At the equator region which receives on average high solar radiation every year, PV/T air-based system is strategically used for agricultural and marine drying process. Othman et al. [58] explained these applications possibly could increase the aspects of social awareness to the public, especially on the environment, wealth creation, nation building as well as sustainable development for the country. Fudholi et al. [59] also mentioned drying up of agricultural and marine products as one of the most attractive and cost-effective applications for solar PV/T technology.

The study of PV/T water-based system starts when the air-type of PV/T has a major problem regarding temperature issue. At four season countries, standard operating for the PV/T air-based system is at temperature 20 °C. The ambient temperature is normally high during summer at low altitudes. Even though the cost of water-based system is more compared to air-type system, it is still more practical to work out the drawbacks of air-based system. Furthermore, PV/T water-based systems function more efficiently due to their higher density than air and they can be used during all seasons. The system is mostly used for generating hot water for domestic applications. Garg et al. [60] analyzed a conventional forced circulation for water type using a pump. The pump enhanced water flow to reach the optimum flow rate, which affects the collector efficiency. Following that, Bergene and Lovvik [61] introduced a physical model and algorithms for quantitative predictions of the system operation. They utilised a sheet and tube design concept on the PV module by adding fins. An overall efficiency of 60–80% is claimed to be achieved in this work.

The fundamental design of PV/T water-based system is sheet-and-tube where a flat-plate PV module is attached on top of a cylindrical-insulated pipe. Chow [62] introduced an explicit dynamic model to study single-glazed sheet-and-tube collector performance. The analysis highlighted the importance of having good thermal contact between the encapsulated solar cells, absorber plate and water tubing. Other than that, several publications are referred to investigations on the mode of water circulation, types of pump and types of absorber. This includes aluminium hollow tube shape, copper hollow tube shape, single-glazed flat plates with fins, square/rectangular shape, direct flow design, serpentine flow, oscillatory flow, spiral flow and web flow designs [63–66]. Ibrahim et al. [63] performed simulation on seven design configurations of water absorbers which are attached underneath the flat plate thermal collector with a single glazing sheet. Under a controlled solar radiation of 600 $W/m^2$ and fluid flow rate of 0.01 kg/s, spiral flow design proved to be the best design with the highest thermal efficiency of 50.12% and corresponding cell efficiency of 11.98%.Figs. 6–8

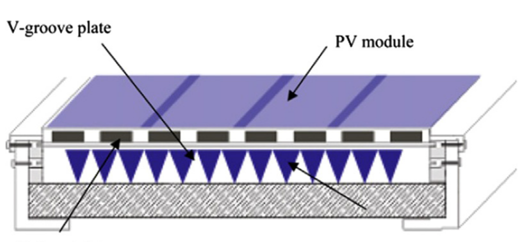


**Fig. 6.** Schematic diagram of PV/T collector with V-groove absorber collector [23]. Cross-section of bi-fluid type PV/T design collector [37].

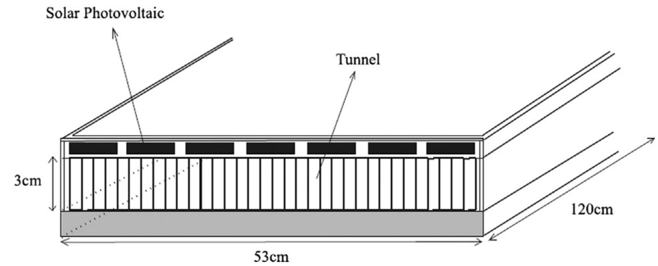


**Fig. 7.** Schematic diagram of PV/T collector with rectangular tunnel absorber collector [23].

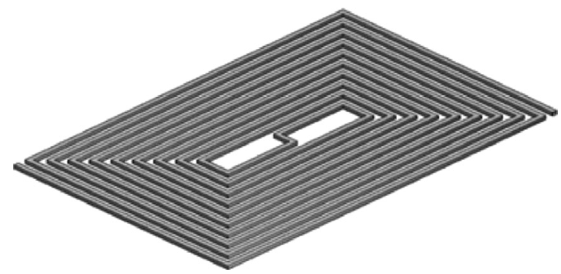

**Fig. 8.** Construction of spiral flow design [63].

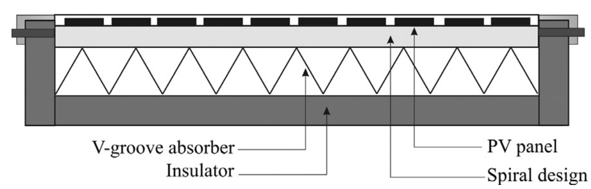


**Fig. 9.** Schematic diagram of PV/T Combi with spiral and V-groove design for water and air absorbers, respectively.

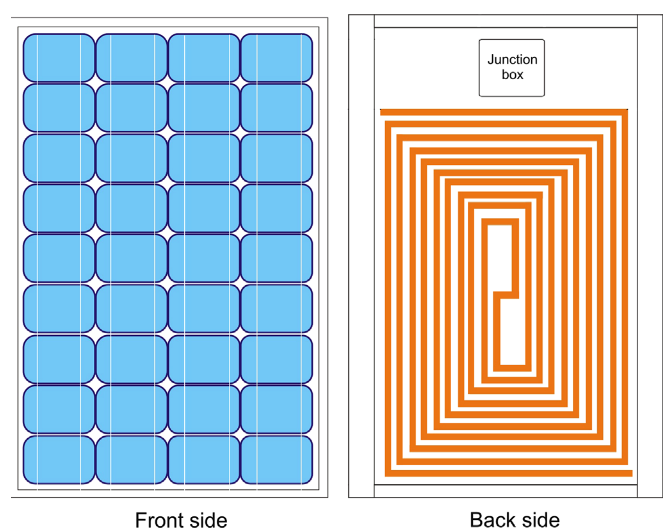


**Fig. 10.** Position of spiral absorber underneath the PV module.

## 3. An overview of PV/T combi

Photovoltaic-thermal combination system (PV/T Combi) is a PV/T system merging two types of heat carriers in one arrangement. Air and water types are chosen since they are practical and mostly studied in previous works by separate systems. PV/T Combi

system also is known as PV/T bi-fluid or dual system [25,68–70]. The idea was first introduced by Tripanagnostopoulos in 2001 at the 17th European PV Conference, Germany [67]. However, the detailed study of PV/T Combi was released six years after that. Basic operation of the Combi system is similar to the individual air and water-based system. In general, both types of medium absorber are placed underneath the PV module.

The system operated such that air and water with the initial setting of temperature and mass flow rate are pumped in and out of the collector. Through convection process, the heat on the PV panel will be absorbed and transferred to the heat exchangers medium. This unwanted heat from the PV panel is extracted and transformed to useful hot air and hot water. This thermal production is stored and used according to the energy needs and applications. Figs. 9 and 10 show an example of arrangement of a single-channel PV/T Combi system. Spiral design water absorber is placed at the centre, between the PV module and the V-groove air absorber. The spiral absorber is attached directly underneath the module to ensure zero air gaps.

The advantage of the PV/T Combi is the output not only can generate electricity, but also can produce hot air and hot water simultaneously. By having two types of cooling mediums in one system, the temperature of the PV panel will be reduced and cell efficiency will be greatly improved at an instant. The use of both fluids also creates a greater range of thermal applications and offers in which hot and/or cold air and/or water can be utilised depending on the energy needs and applications. Currently, PV/T Combi is still under-explored by few interested researchers. The following sub-section will provide an overview of the PV/T Combi system that has been published.

### 3.1. PV/T combi I

In 2007, an article published by Tripanagnostopoulos [25] introduced six design constructions of a dual system. The main idea of the combined system is to cover the limitations faced by the PV/T collector for both water and air heat exchanger modes when they are operated separately. Table 1 states the pros and cons of both PV/T collectors as reported. The operation of the combined system also can be switched among hot air and hot water depending on the weather conditions and building requirement. Interestingly, combinations of air and water based on one system improved the air heat extraction (AHE) due to the placement of pipes in each design. The article reported that water heat extraction (WHE) on the pipes enhanced the heat-exchanging

**Table 1**
The advantages and disadvantages of PV/T water and air modes.

| PV/T system | Advantage | Disadvantage |
|---|---|---|
| PV/T water collector | Efficient operation at low and medium latitudes with favourable weather condition | Less efficient operation at high latitude due to freezing problem |
| | | Limitations in system design and operation due to necessary heat exchanger element |
| PV/T air collector | Efficient operation at medium and high latitudes without freezing problem | Less efficient operation at low latitude due to high ambient temperatures and unnecessary during the summer period<br>Less efficient than water-based due to low density of air |

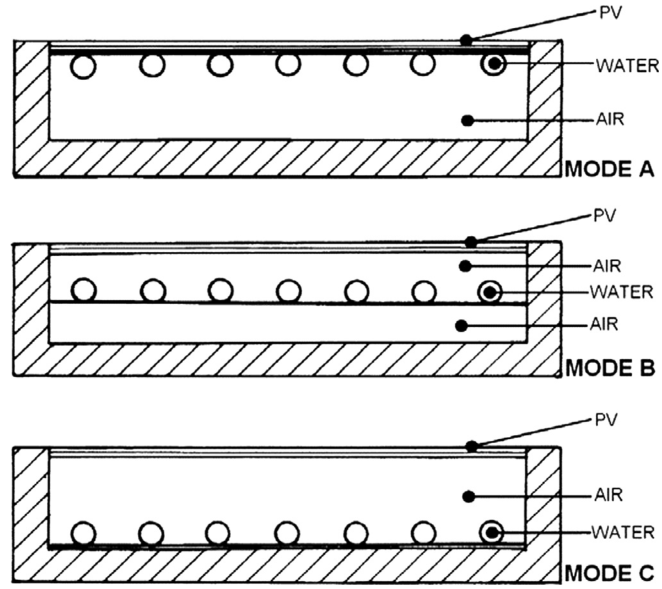


**Fig. 11.** Designs of PV/T dual system [68].

surface through the air channel. Fig. 11 shows the first three modes of PV/T Combi collector with each design being labelled as Mode A, Mode B and Mode C, respectively.

These three models are differed by the position of WHE, which is underneath the PV module (Mode A), in between AHE (Mode B) and at the bottom surface of the air channel wall (Mode C). The design performance is investigated using the experimental method which was carried out at University of Patras, Greece. A pc-Si PV module is used throughout the testing and WHE was constructed from copper sheet and copper pipes. The system is tested under controlled operational parameter solar radiation intensity of variation $\pm 20\ \mathrm{W/m^2}$, ambient air temperature variation of $\pm 1$ K and fluid mass flow rate of 0.02 kg/s. The thermal efficiency $\eta_{th}$ and electrical efficiency $\eta_{el}$ of the solar collector are calculated by the following relations:

$$\eta_{th} = \frac{\dot{m} C_p (T_o - T_i)}{A_a G} \tag{3}$$

$$\eta_{el} = \frac{I_m V_m}{A_a G} \tag{4}$$

where $\dot{m}$ is the fluid mass flow rate, $C_p$ is the heat removal fluid specific heat, $(T_o - T_i)$ is the change of temperature, $A_a$ is the system surface of area, $G$ is the incoming solar radiation, $I_m$ is the maximum current, and $V_m$ is the maximum voltage.

The highest thermal efficiency analysis on WHE was achieved by Mode A, followed by Mode B and Mode C. Regarding AHE, Mode B presents the highest thermal performance with moderate outputs for both Mode A and Mode C. From the overall evaluation, Mode A is the most acceptable and effective combination model of WHE and AHE since it responds higher to thermal performance. This is significantly shown by the arrangement of WHE and AHE of the design in Mode A, where more efficient water heating and PV cooling are produced due to the position of WHE on the PV rear surface. This main production results in higher thermal and electrical output gains compared to the other two modes. Nevertheless, the analysis and results of electrical performance are not discussed in the paper.

Three other different PV/T Combi designs were presented based on further modifications of Mode A to enhance heat extraction in the air circulation. The improvements were made by introducing three low-cost elements: thin metallic surface (TMS), fins and

small ribs. The first modified design is placing the TMS element interjection between the air channels and parallel to air flow. This design is labelled as the PVT/dual-TMS model. The second modified design is mounting a galvanised iron sheet of fins element on the opposite air channel wall (PVT/dual-FIN model). The third modified design is combining the first and second models (PVT/dual-TMS/RIB model). The configurations of the modified designs are shown in Fig. 12.

The length of fin is 4 cm in vertical surface and it is placed along the 1 m air stream in the collector. The function of TMS and fins element is to double up the heat exchange surface area in the air channel while reducing heat transmittance to the back air channel wall [35]. Both elements also promote advantages in terms of obtaining satisfactory air heating, reducing temperature on PV module and lowering the temperature increment at the opposite channel wall. In addition, the TMS element on the design acts as a shield to prevent heat flow from the PV rear surface to the opposite air channel wall. In order to achieve high emittance ($\varepsilon \sim 0.9$), the upper side of the TMS element is painted mat black while the lower side is left unpainted ($\varepsilon \sim 0.1$). This allows more heat to be absorbed on this absorber top surface. Comparing PVT/dual-TMS and PVT/dual-FIN models, black painted ribs which

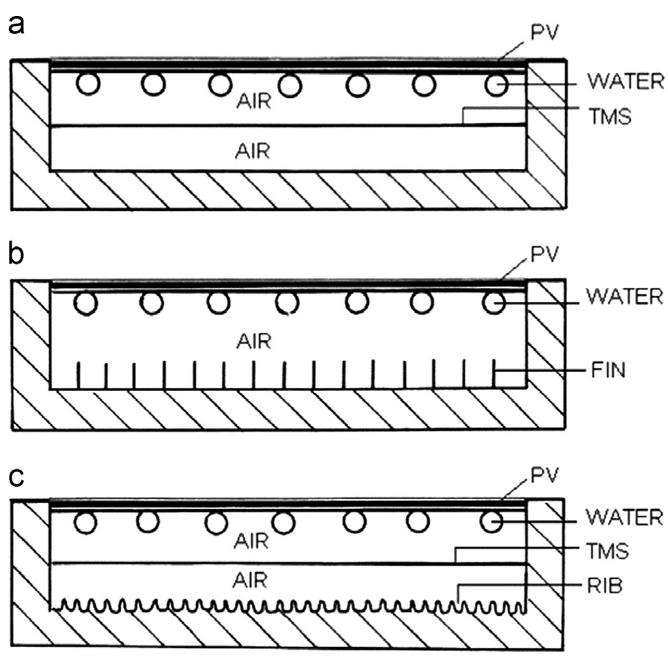


**Fig. 12.** Modified design of Mode A PV/T Combi system. (a) PVT/dual-TMS model, (b) PV/T-dual FIN model and (c) PVT/dual-TMS/RIB model [34].

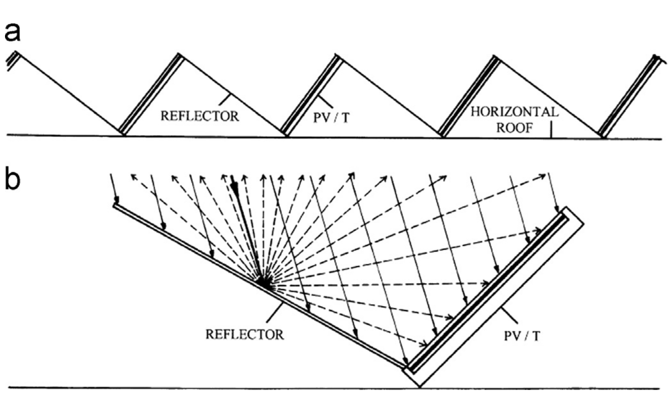


**Fig. 13.** PV/T system with booster diffuse reflectors: (a) horizontal building roof system installation; (b) indication of diffuse reflected radiation on the PV panel [70].

simulate small fins of about 5 mm were formed on the opposite air channel wall of the third design (Fig. 12c). The configuration is aimed to combine the advantages of TMS and FIN modifications. The black ribs enhance the radiation of heat transmission from the TMS back surface to the air channel wall and overcome the lower heat transfer from wall to circulating air.

The outdoor experiment was carried out using similar methodology with the previous batch except that it was added up with additional incident solar radiation [68]. A flat-stationary diffuse reflector of a mat thin aluminium sheet was attached on a rigid thin wooden sheet and adjusted to the sun (Fig. 13). This installation increased the solar radiation on the PV module as it provides almost uniform distribution of the reflected solar radiation on the PV surface. In a different paper, the aluminium diffuse reflector was shown to increase the incoming solar radiation on PV surface up to 50%, resulting to 25–35% increment on electrical output at the operating temperature of 40–70 °C, respectively [69]. Other interesting factors are based on its cost effective and easy construction with typical size of the PV panel.

The experimental results of the modified models are compared with Mode A. For the air heat extraction, the thermal output of the modified designs showed a substantial increase which is higher by 23%, 33% and 36% for PVT/dual collectors with TMS, FIN and TMS/RIB, respectively. Contrasted with water heat extraction, the increment is only in a smaller margin, which differs by 17%, 16% and 14%, respectively. Under low operating temperature, the addition of flat diffuse reflector enhances the electrical performance by 12%. Overall performance shows that the combination of two heat extraction systems with simultaneous operation complements each other. The application of a TMS modification system is more suitable for building protection from overheating, the FIN modification is more to gain thermal output while the TMS/RIB modification is fit for both applications. All designs presented in the paper are claimed to be cost-effective solar energy devices, efficient as building integrated and are promising technologies for broader applications in the PV arena.

### 3.2. PV/T combi II

Another design of the PV/T Combi collector which was also named as bi-fluid type PV/T collector was presented in 2007. Assoa et al. [70] presented a steady-state two-dimensional thermal model for the design shown in Fig. 14. The Combi collector design is innovated from the sheet-and-tube concept and utilised the corrugated rib steel sheet section by installing evacuation tubes in the ribs. The cold/hot water is flown through a copper tube insulated with a cellular rubber half-cylinder. The air heat exchanger is placed between the absorber and the insulation layer. The configuration can provide extra production of hot water and it can be installed to the basic PV/T air collector as an option, depending on the energy needs of the building. PV cells and the absorber surface are designed in juxtaposition, which is in contrast with the conventional PV/T collector system where the panel surface is used

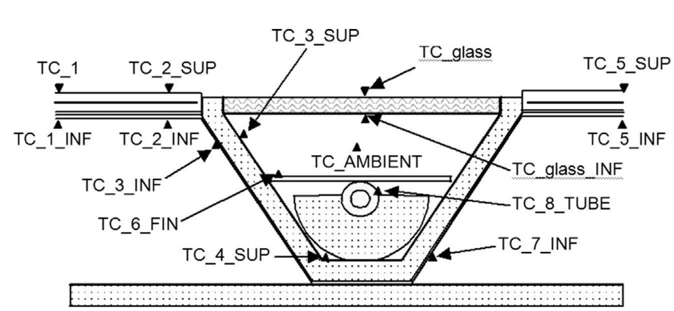


**Fig. 14.** Cross section of bi-fluid type PV/T design collector [71].

as the absorber. The reason is to protect the PV cells and the resin from premature ageing in the long term. A fin in 15° inclined configuration is to separate the air zone in the air gap and the rib.

The electrical ($\eta_{el}$) and thermal ($\eta_{thw}$, $\eta_{thair}$) performances are analysed accordingly based on the following equations:

$$\text{Electricalefficiency}: \eta_{PV} = \eta_{ref}[1-\beta(T_{ecell}-T_{ecellref})] \tag{5}$$

$$\text{Thermalefficiency (for WHE)}: \eta_{thw} = \frac{q_{mw}C_{pw}(T_w - T_{win})}{GL(b_{abs}/2)} \tag{6}$$

$$\text{Thermalefficiency (for AHE)}: \eta_{thair} = \frac{q_{mf}C_{pf}(T_f - T_{fin})}{GL(b_2/2)} \tag{7}$$

where $\eta_{ref}$ is the reference cell efficiency (0.12), $\beta$ is the coefficient of module temperature, $q_{mw/f}$ is the mass flow rate of water/air, $C_{mw/f}$ is the specific heat of water/air, $L$ is the collector length, $b_{abs/2}$ is the width of water/air absorber, $T_{ecell}$ is the temperature of PV module surface, $T_{ecellref}$ is the reference operating temperature of PV cells (25 °C), $T_w$ is the temperature in water tube, $T_f$ is the temperature in air gap, $T_{win}$ is the temperature of inlet water, and $T_{fin}$ is the temperature of inlet air.

The simulation results are then compared with experimental data to confirm the validity of the model for a forced ventilation of the air gap and a laminar water flow. A good agreement was achieved with less than five per cent relative difference between both results. The system performance is evaluated based on important parametrical variables, which are collector length, fluid mass flow rate, cells efficiency and thermal efficiency. It is tested under fixed experimental conditions: solar radiation, $G$=625 W/m$^2$, ambient temperature, $T_a$=36.3 °C, mean velocity of air gap ventilation, $V_{air}$=5.5 m/s, inlet air temperature, $T_{fin}$=24.7 °C, inlet water temperature, $T_{win}$=25.5 °C, wind speed, $V_{air}$=5.5 m/s and water mass flow rate, and $q_w$=5.9 × 10$^{-4}$ kg/s.

The collector length is tested with three different lengths of 2.7 m, 10 m and 20 m. As the length increased, the temperature of the solar collector significantly increased. Air temperature is rapidly increased from 30 °C up to 67 °C. The increment of water temperature is less by about seven times that of air temperature but reached the maximum approximately 80 °C at maximum collector length. This may due to the distance of water pipe which is close to the absorber so that more heat is extracted by this heat carrier medium. The influence of fluid mass flow rate on solar collector temperature shows an opposite response compared to collector length effect. Both flow rate and collector temperature give negative exponential relationship with decrement variation of 30–40% (AHE) and 0–5% (WHE). Air mass flow rate shows a weak influence on the water temperature due to efficient heat conduction at the fin. However, the water mass flow rate just contributes minor influence on air temperature at the exit of the gap.

In contrast, the fluid mass flow rate shows a very good correlation to thermal efficiency. The shortest collector length provides the best increment with approximately 85% and 80% efficiencies at 0.018 kg/s and 0.2 kg/s of water and air mass flow rate, respectively. As the air mass flow rate increased, thermal and electrical efficiencies for both air and water modes are increased. But as the water mass flow rate increased, only the water-mode collector shows good behaviour of the efficiencies. Again, water-mode heat extraction showed the best performance due to its closed position with the absorber. Electrical efficiency gained in the study is 12%, which indicates the cooling of the PV cells is satisfactory and can be improved. The application of this thermal output is concentrated on solar cooling devices during summer and direct domestic hot water (DHW) to the residential area.

### *3.3. PV/T combi III*

Earlier in 2003, Zondag et. al [71] classified the flat plate types of PV/T design into four categories. Mainly, they are (i) Sheet-and-tube PVT collectors, (ii) Channel PVT collectors, (iii) Free-flow PVT collectors, and (iv) Two-absorber PVT collectors. In order to compare the total efficiencies and overall performance of the system, nine different designs of PVT collectors have been introduced. The schematic diagram of the general classifications is shown in Fig. 15 while the derived designs are listed in sequence table (Table 2).

The sheet-and-tube PV/T collector is innovated from the integration of thermal collector with a conventional photovoltaic panel. Three designs of sheet-and-tube are examined, namely uncovered, one-cover and two-cover PV/T collector. The ideas give good impact on heat generation based on multiple reflections of sunlight occurring on the covers. Although the increment number of cover gives positive proportional relationship on the thermal efficiency, yet the electrical performance has a drastic decrease due to the high temperature on the PV surface. Designs with two or more cover are not relevant for the application since the electrical efficiency is greatly reduced.

The channel PV/T collector highlights the suitable absorption spectrum of fluid type. The selection has to be different from

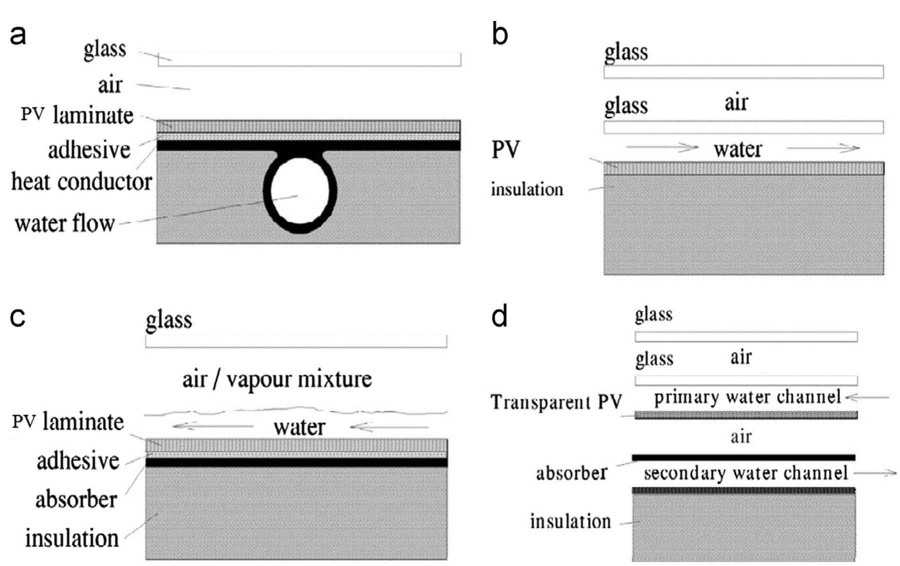


**Fig. 15.** Groups of PV/T collectors: (a) sheet-and-tube PV/T, (b) channel PV/T, (c) free-flow PV/T and (d) two-absorber PV/T [72].

**Table 2**
Nine different design concepts of PV/T Combi collectors.

| PV/T collectors classifications | Design concepts | |
|---|---|---|
| (a) | Sheet-and-tube: | 1. Uncovered sheet-and-tube PV/T collector<br>2. Single/one-cover sheet-and-tube PV/T collector<br>3. Double/two-cover sheet-and-tube PV/T collector |
| (b) | Channel: | 4. Channel above PV<br>5. Channel underneath opaque PV<br>6. Channel underneath transparent PV |
| (c) | Free flow: | 7. Free-flow PV/T collector |
| (d) | Two-absorber: | 8. Insulated two-absorber PV/T collector<br>9. Non-insulated two-absorber PV/T collector |

**Table 3**
Calculated thermal and electrical efficiencies at zero reduced temperature [71].

| Panel type | Thermal efficiency | Electrical efficiency |
|---|---|---|
| PV laminate | – | 0.097 |
| Uncovered sheet-and-tube PV/T collector | 0.52 | 0.097 |
| Single/one-cover sheet-and-tube PV/T collector | 0.58 | 0.089 |
| Double/two-cover sheet-and-tube PV/T collector | 0.58 | 0.081 |
| Channel above PV | 0.65 | 0.084 |
| Channel underneath opaque PV | 0.60 | 0.090 |
| Channel underneath transparent PV | 0.63 | 0.090 |
| Free-flow PV/T collector | 0.64 | 0.086 |
| Insulated two-absorber PV/T collector | 0.66 | 0.085 |
| Non-insulated two-absorber PV/T collector | 0.65 | 0.084 |
| Thermal collector | 0.83 | – |

absorption spectrum of photovoltaic so that the incoming radiation can shine efficiently on PV. The first design allowed water to flow on top of the PV panel since it has a small overlap in absorption with PV and the 4% decrement in electrical yield effect can be neglected. The weakness of the design is observed when the fluid channel becomes wider. It caused the usage of thick glass cover to withstand the water pressure, which resulted in a heavy and fragile construction. To overcome this problem, two more designs are tested which are channel below underneath opaque PV and channel underneath transparent PV panel. These designs can obtain higher thermal and electrical efficiencies because they allow water to flow underneath the PV module. This totally can solve the water pressure on top of PV as well as construction issues that arose at the earlier part of the study. Safety step has been taken where the construction at the backside of the system must be sufficiently watertight to avoid leaking. The opaque PV has an extra advantage on this since it is already strengthened with a metal back.

The free-flow PV/T collector design is a modification of channel designs. By removing one layer of glass cover, it reduced the technical, mechanical and costing issues faced originally by channel designs. Water-type is still used in this system design because it is a natural choice and is transparent that does not affect the solar spectrum absorbed by the PV module. Nevertheless, the modification design caused an increment of heat loss due to evaporation pressure caused by the water. This is obvious when the system is operated at higher temperatures due to high evaporation pressure of the water. The solutions for this issue are adding a transparent insulating layer in sandwich between the primary and secondary channels and replacing the secondary channel with sheet-and-tube configuration.

The two-absorber PV/T collector uses a transparent PV laminate on the primary channel and a black metal plate on the secondary one. The absorbers are placed underneath each channel which performed as a double pass system. The upper channel allows fluid to flow in, while the lower channel is for fluid to flow out. Such a construction indicates higher thermal efficiency. Unfortunately, the problem of this design is twice that of channel PV/T collector due to the usage of two absorbers.

Even though the described designs are well known as water-type categorisation, the existence of air flow in each design cannot be neglected. On the configuration, both water and air mediums act as heat carriers. Therefore, the specified technologies match the criteria of PV/T Combi and only water-type performance is presented in the paper. The overall performance of the designs is critically analysed through optical and thermal modelling as well as prototypes testing on field. The experimental results were obtained using lab equipment built at the Eindhoven University of Technology, The Netherlands [72]. It is tested for a domestic hot water system. Only single sheet-and-tube is tested as a prototype. The selection is based on manufacturing and process performance criteria.

The optical modelling determines the amount of irradiation hit on the PV/T collector systems. A transmission-absorption of the collector $\tau_\alpha$ is calculated from here which then is inserted into the thermal modelling that is required to analyse heat flow within the collector. Combinations of both models can evaluate the thermal performance of all the PV/T collector systems and the equation is the same as shown in Eq. (3). The electrical efficiency is calculated as demonstrated in the following equation:

$$\eta_{el} = \eta_o[1 - 0.0045\ (T - 25\ ^{\circ}\mathrm{C})] \tag{8}$$

where $\eta_o$ is the reference cell efficiency (0.097), and $T$ is the cell temperature.

Table 3 shows the thermal and electrical efficiencies at zero reduced temperature based on the modelling results. Uncovered sheet-and-tube design showed the poorest and best thermal and electrical performance, respectively. This is because of the zero cover on the PV surface that allowed heat to lose instantaneously by absorbing solar irradiation at a great amount without any secondary reflection issue. This gives uncovered sheet-and tube as a recommended application at low temperature. The other two sheet-and-tube designs produced better overall performance than the first. The two covers configuration is concluded to operate efficiently at high temperature due to the substantially degraded on the electrical efficiency with minor increment on the thermal efficiency. The other five presented designs show better overall performance than the sheet-and-tube. The channel type in the configurations contributes to excellent heat transfer properties. Specifically, the free-flow design which has evaporation issue with water type is convenient to operate at low reduced temperatures only. Another different liquid type has to be proposed if the system needs to work at higher reduced temperature.

Single cover sheet-and-tube is chosen as the most promising design concept for domestic hot water generation although it is 2% lesser than the channel underneath transparent PV. It has also been selected due to the easy construction and the availability in the market. This is supported by the European PVT Roadmap [73] which claimed the design as a main market product for PVT collectors. A multi-crystalline silicon PV panel is attached on top of the absorber. The single cover is separated with a PV panel by one-layer air gap and the tube is placed at the rear surface of PV module covered by the insulation system. The measurement obtained shows a good agreement with the modelling results within the range of the experimental data.

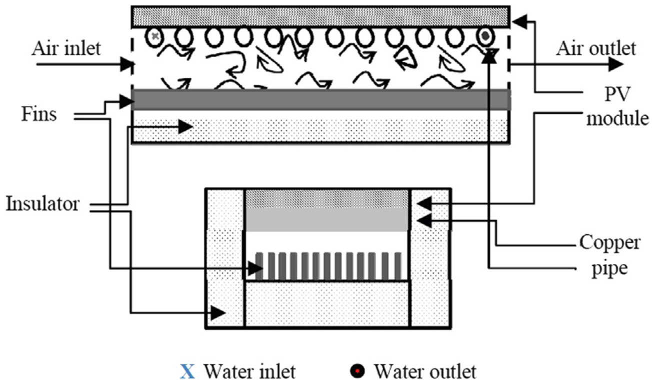


**Fig. 16.** Top: side view. Bottom: front-view of the designed bi-fluid PV/T system [75].

### 3.4. PV/T combi IV

A research group from Malaysia performed a design concept and mathematical modelling of a bi-fluid PV/T solar collector [74]. The design is constructed with serpentine-corrugated surface attached underneath the PV module, a single pass air channel and additional fins at the rear surface of the air channel. The serpentine configuration is shaped by copper pipe which is exposed to the air channel to serve as transverse corrugated surface to the airflow. The pipe surface is coated with black paint to enhance the emissivity of the copper pipe due to the low heat capacity of air. The selection of serpentine is based on the previous study that has been proven sufficient and able to sustain the flow uniformity in the pipe [63,75]. The addition of fins which was positioned in parallel with airflow is to heighten heat transfer rate by creating cross-corrugated configuration. The schematic diagram of the design system is shown in Fig. 16 with side and front view perspectives. The working equations to determine electrical and thermal efficiencies are shown in the next formula. Total thermal efficiencies are calculated by adding thermal efficiency of both air and water together.

$$\eta_{el} = \eta_o[1-\beta(T_{pvave}-T_{ref})] \tag{9}$$

$$\eta_{thtotal} = \frac{\dot{m}_{f1}C_{f1}(T_{f1o}-T_{f1i})+\dot{m}_{f2}C_{f2}(T_{f2o}-T_{f2i})}{A_cG} \tag{10}$$

where $\eta_o$ is the reference cell efficiency, $T_{pvave}$ is the average cells temperature, $T_{ref}$ is the reference temperature, $A_c$ is the collector surface area, $\dot{m}_{f1/2}$ is the fluid mass flow rate for air/water, $C_{f1/2}$ is the heat removal fluid specific heat for air/water, and $(T_{f1/2o}-T_{f1/2i})$ is the change of temperature for air/water

The analysis of the design is run through MATLAB software using two-dimensional steady-state finite difference method. The calculations procedure has been improved by the authors in different presented papers [76–78]. The thermal model is tested for two conditions: with and without working fluid. Significant results are shown when simulated for working fluid conditions are operated either individually or concurrently. It is also shown that the overall energy efficiency of this bi-fluid working system is higher than without the working fluid PV/T system. At $\dot{m}_{f1}=0.034$ kg/s and $\dot{m}_2=0.0079$ kg/s, the average temperature of PV cells drops, which gives good correlation to the cell efficiency. Another tremendous achievement obtained is the increment of electrical power by 32.6% which is significant in the range of 500–800 W/m$^2$. All this shows the bi-fluid PV/T system able to double up the heat extraction from PV cells. The aim of the paper is not only to improve electrical performance, but also proposed to fully utilise the thermal energy for various applications such as agriculture drying process, fish breeding water heating and also domestic drying usage.

## 4. Further discussion on PV/T combi system

Overall, the PV/T Combi system discussed in this paper shows significant responses on electrical and thermal performance. It is proven that combining two types of heat exchanger, namely air and water, contributes to low temperature on the PV module surface. Thermal efficiency from all overviewed papers is extremely high, which leads to the accomplishment of great improvement on electrical efficiency. This is definitely attained from the double heat extraction from both air and water collector.

The total efficiency of the combination system is not well explained by all the papers. From the authors' understanding, some of the papers had determined the total efficiency of the operating system through energetic analysis derived from the First Law of Thermodynamic [53]. There is also a study using exergetic analysis derived from the Second Law of Thermodynamic by knowing the fact that electrical and thermal energy cannot be considered having the same “quality” although they are same in “quantity” with a similar physical unit [79–81]. These two approaches' analysis is still relevant to be used depending on the priority of the research. Hence, the overall efficiency of the PV/T Combi system for each presented design is not discussed in this paper.

All the PV/T Combi systems overviewed differ by their design and configuration. As shown in PV/T Combi designs I and III, the systems are tested with various arrangements of the absorbers. Either the position is on top or underneath the PV module, and they still give good reflections to the PV cells' performance. Additional cooling effect materials provide a fascinating approach in decreasing the temperature of PV cells. This includes TMS, fins and ribs as has been described in PV/T Combi designs I, II and IV. They are commercially available in the market at low cost and feasible construction.

However, the combination system of PV/T collector still is not very interesting to researchers. This may due to the complicated construction than the individual PV/T collector system, high cost and maintenance issue. Looking back at the remarkable thermal and electrical performance offered by this PV/T Combi system, one can consider exploring the system so that it can be improved in many aspects. The combination of both systems as one unit also provides more architectural uniformity by aesthetical design and contributes to reducing the payback period. Although an attempt has been made to make this paper as complete as possible, it is inevitable that some of the relevant research is missed in this compilation.

## 5. Conclusion

The contributions of sustainable solar energy in providing every need to the Earth are very valuable. Many studies had been conducted in order to fully utilise the special benefit solar energy had to offer. Nowadays, most of the countries contribute full commitment to legally binding emission targets including policies to encourage renewable generation. The ingestion also contributes to how much and how severely the environment can be affected. It is really remarkable to see that solar technology can fully replace the current source of energy and can be accepted by humankind in future.

A brief overview on the literature and the aspects of studies in terms of technologies and improvements of PV/T Combi solar system has been presented. The upgrading system by combining both types of heat carrier modes allows better performance of the PV/T technology as well as allows gaining higher efficiencies. The combination of the two systems is also to cover the limitations and weaknesses of independent PV/T water and air heat collector

systems. This is especially on ambient operating temperature and gaining better thermal and electrical efficiencies. The outcome of the system can be beneficial to humankind due to its efficient application in domestic and industrial sectors.

The big challenge in this study is to harness the Sun to the maximum limit so that performance of the PV/T system can allow better performance on the efficiencies. Combination of these two collectors is just like a marriage made in heaven. The teamwork completes each other in terms of reducing the lack of each separate system drawback, gaining higher overall efficiencies as well as solving the operation cost and payback period issue.

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